DARPA STTR Phase I Final Report

Virtual Assembly of Microsystems

July 26, 2000

Sponsored by
Defense Advanced Research Projects Agency
Defense Logistics Agency
Defense Contract Management Command Baltimore-Norfolk
200 Granby Street, Room 339
Norfolk, VA 23510-1811

ARPA Order C043, Amdt.26

Issued by U.S. Army Aviation And Missile Command Under
Contract No. DAAH01-99-C-R211

Name of Contractor:	Analytical Mechanics Associates, Inc.
Business Address:	17, Research Drive, Hampton VA 23666
Effective Date of Contract:	July 6, 1999
Contract Expiration Date:	July 6, 2000
Principal Investigator:	Sankar Jayaram
Phone Number:	(509) 335-3145
Short Title of Work:	Virtual Assembly of Microsystems
Reporting Period:	July 6, 1999 to July 6, 2000

Disclaimer

"Approved for public release; distribution unlimited"

DECLARATION OF TECHNICAL DATA CONFORMITY

The Contractor, Analytical Mechanics Associates, Inc. , hereby declares that, to the best of it's knowledge and belief, the technical data delivered herewith under Contract No. DAAHO1-99-C-R211 is complete, accurate, and complies with all requirements of the contract.

Date July 26, 2000

Name and Title of Authorized Official Dr. Hans Seywald.

Hans Seywald 7-26-00

Table of Contents

1. Summary of Phase I Research Results

All Phase I research objectives were met or even exceeded. An integrated prototype software application was created based on the theoretical results developed during the course of the project. While using this software environment, members of our team became the first humans to "feel" the interacting forces between micro and nano scale objects.

During the course of the project, it became clear that the computational burden involved in the exact modeling of the relevant physical forces constitutes a major challenge. Clearly, the introduction of more and more powerful computers will continuously extend the realm of solvable problems. Quite naturally, however, the user will always have the desire to take his application to the next level and treat an even more elaborate problem. Several ideas to further speed up the calculation of the physical forces were developed during the Phase I research. These ideas will be further investigated in Phase II and implemented in a production software environment.

2. Discussion of Phase I Research Results

In Sections 2.1 –2.8, the findings of the tasks outlined in the Phase I proposal are discussed.

2.1 Task 1: Evaluate the state of the art in VR-based virtual assembly and understand the issues confronting the deployment of virtual assembly for IPPD

The following is a summary of the various leading activities in VR-based virtual assembly.

Virtual Assembly Design Environment (VADE) [Jayaram 1999] has been designed and implemented at Washington State University in collaboration with NIST. This system supports several types of physically-based modeling methods to allow engineers to simulate interactively the assembly of medium and large sized mechanical systems (automotive, heavy machinery, etc.). Archimedes [Kaufman1996] is an assembly planning research project in the Intelligent Systems and Robotics Center, or ISRC, at Sandia National Laboratories. Archimedes which creates an assembly plan based on a CAD assembly. Engineering Animation Incorporated (EAI)[WWW02] markets products that model and simulate manufacturing and production line processes including assembly. The focus of EAI's work pertaining to virtual assembly has been on simulating and evaluating dimensional variation issues in product assembly. Work at Heriot-Watt University [WWW05] in the field of virtual assembly has focused on two areas. The first is the use of immersive virtual reality to design and plan cable harness layouts. The second focus of virtual assembly at Heriot-Watt University is the use of virtual reality to extract elicit knowledge from the user for assembly planning.

Work at Carnegie Mellon University developed into an "Intelligent Assembly Modeling and Simulation" environment (IAMS) [Gupta 1997]. IAMS is an intelligent environment in which simple simulation tools can be composed into complex simulations for detecting potential assembly problems. Deneb Robotics, Inc., has produced a product called Deneb/Assembly [WWW04] to aid in Design For Assembly tasks. Deneb/Assembly is a engineering tool used to capture part paths, detect collisions, generate collision-free paths, inspect internal parts and clearances, simulate cable and wire harnesses, and generate shop floor instructions. Research at the University of North Carolina in Chapel Hill, North Carolina, has been focused on a project called the nanoManipulator [WWW03]. The researchers are developing an improved, natural interface to scanning probe microscopes, including Scanning Tunneling Microscopes (STM) and Atomic Force Microscopes (AFM). The nanoManipulator (nM) couples the microscope to a virtual-reality interface to provide a telepresence system that operates over a scale difference of about a million to one. The nanoManipulator has been used to examine viruses and other micro scale structures.

2.2 Task 2: Evaluate existing methods for simulating the forces experienced during the assembly of In2m devices

The relative importance of external forces on a MEMS device is very different from that in the macro world. Unlike with traditionally sized parts, gravity is not the dominant force acting on a MEMS device. As components become smaller than 1 millimeter, gravity is almost negligible, while surface adhesion, electrostatic, electromagnetics, and van der Waals forces dominate (See Figure 1). These forces are visible during the fabrication, assembly, and operation of all MEMS devices. During wet etching operations, these forces cause freed structures to be attracted to one another. During the assembly of hybrid MEMS, these forces cause MEMS components to adhere to tools. During operation of MEMS devices, these forces act as highly nonlinear friction terms.

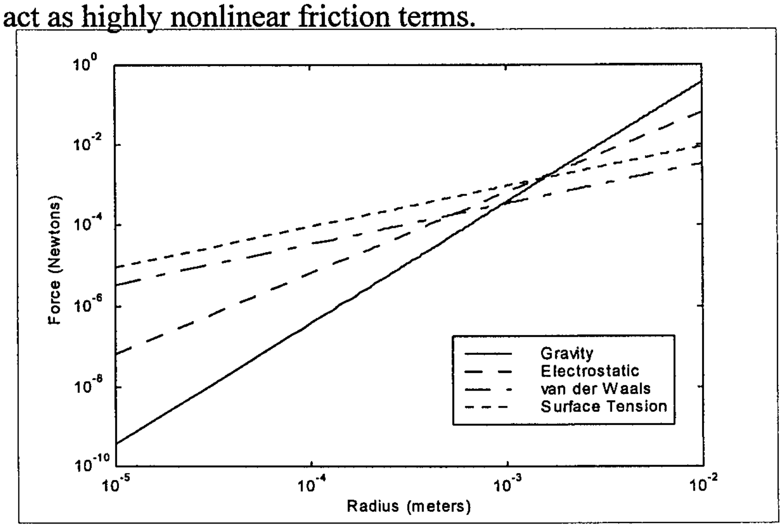

Figure 1. Forces of attraction between a sphere of a given radius and a plane.

In the research literature, most of the work in this area has been performed by particle physicists who are interested in the adhesion of sprayed (often spherical) particles onto flat objects. For forces such as van der Waals, there are closed form analytical solutions for very simple geometrically shaped objects such as the interaction between two spheres or a sphere and a half space. However, finite element codes that predict the van der Waals force between arbitrarily shaped objects do not exist. Similarly, there exist formulas for surface tension between simple shaped hydrophilic surfaces, but not for complex shapes. In the area of electrostatics, several finite and boundary element codes exist. However, these codes are typically used to estimate the capacitance between objects, and not the interfacial forces.

Within Phase I of this project, we modified a Sandia-developed boundary element electrostatics code, called EIGER_S, to calculate the forces of interaction between arbitrarily shaped metal parts. Solid models of the parts where created in SolidWorks, and meshed surfaces were generated using the commercial package Ideas. The virtual reality environment displayed the solid model from the SolidWorks, while the EIGER_S code determined the forces acting on the meshed surfaces.

2.3 Task 3: Evaluate the level of physically-based modeling required to adequately simulate the interactions between objects

The interactions between objects during the assembly of In2m devices can be broken down into two types: a) forces of interaction when the objects are close to each other, and b) forces of interaction when the objects touch or collide with each other. Both types of forces are important in simulating these assemblies and the forces in the transition zone are particularly difficult to simulate. This phase of the project focused on the electrostatic forces between objects and the forces of collision.

The process of solving for and displaying the electrostatic forces in MEMS assembly involves four steps. The first step is to obtain a boundary element solution for the electrostatic forces. This involves obtaining a solution at multiple points, which maps out a working volume. Currently, forces and moments are calculated throughout this working volume for the electrostatic interaction of the MEMS component (work piece) and the tweezers (tool) used in the assembly process. The solution is obtained at each point in the working volume for multiple orientations of the work piece and tool. The combination of these orientation and position solutions creates a full six degrees of freedom solution grid. The computational time required for each calculation prevents the solutions from being calculated and displayed at or near real time. Therefore, the second step in the process involves performing a real-time interpolation of the electrostatic forces based on the current relative position and orientation of the tool to the work piece. This interpolation provides us with an approximation of the forces and moments as we move through the virtual MEMS assembly environment. The third step of the process is the application of a scaling factor to the forces and moments in order to display them to the user at a level that can be felt and

interpreted. The fourth step of the process is to perform a force analysis of the system to decide if the electrostatic forces of attraction are great enough to cause the work piece to move towards or stick to the tool or any other object in the environment. When the work piece is attached to the tool, the tool is allowed to move the work piece throughout the environment until an analysis of the forces acting on the work piece causes it to free itself from the tool. Figure 2 shows a typical tweezer/work piece combination for MEMS assembly.

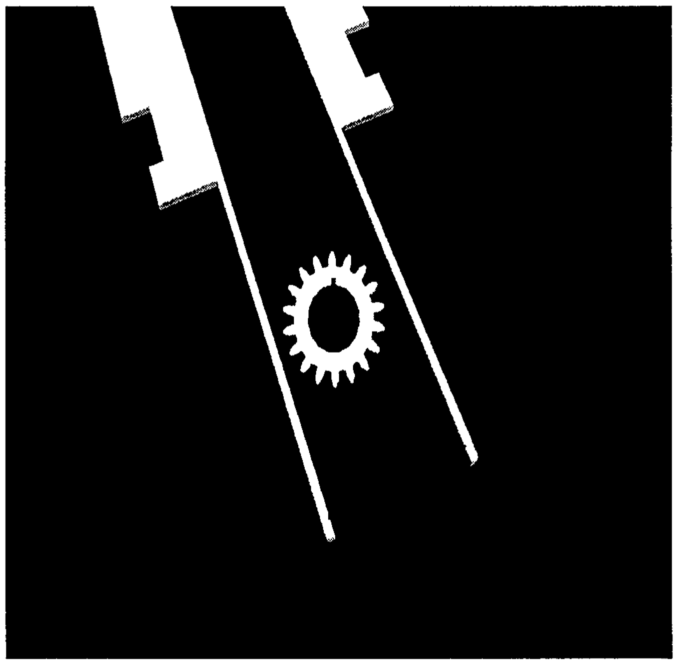

Figure 2. Moving tweezers close to the micro-gear.

A boundary element electrostatic program called EIGER_S is being used to solve for the micro-scale forces and moments between two bodies (a gripper and the part to be grasped). This software was originally developed by Sandia National Laboratories to evaluate the electrostatic fields on various weapons components. In this project, we have added the capability to compute the electrostatic forces and moments between multiple bodies.

2.4 Task 4: Investigate methods for real-time computation of interaction forces for display in the virtual environment

A promising approach to speed up the calculation of the electrostatic forces and moments was developed. This approach is based on an idea that enables a computationally inexpensive calculation of the sensitivities of the electrostatic field with respect to changes in the configuration. These

sensitivities are then used in a linear extrapolation scheme. Details of this approach are discussed in the AMA report [Seywald, 2000].

2.5 Task 5: Create methods to "display" the forces of interaction using multi-modal VR environments

The solutions of the boundary value equations give us forces on the order of 10^{-9}N. Obviously, forces this small are not naturally felt by humans. Therefore, a scaling factor needs to be used to scale these forces up to human scale. When we do this we must keep in mind that there are two types of forces that we will feel as users of this system. The first type of force is the electrostatic force that is calculated by the boundary element solution, the second type of force is the contact force of our tool colliding with another object in the environment. Contact forces are reaction forces and are determined by using friction factors and force vector balances. Contact forces between the tool and a MEMS component also need to be scaled in order to achieve a force resolution that we, as human users, are capable of detecting. When determining what the scaling factor must be, we have to keep in mind that there sometimes needs to be a transition from electrostatic forces to contact forces. This is especially true since the electrostatic forces are discharged to zero when the two objects come in contact.

SensAble Technologies' PHANToM device provides three degree of freedom force feedback to a user through the use of servo motors and lever arms (Figure 3).

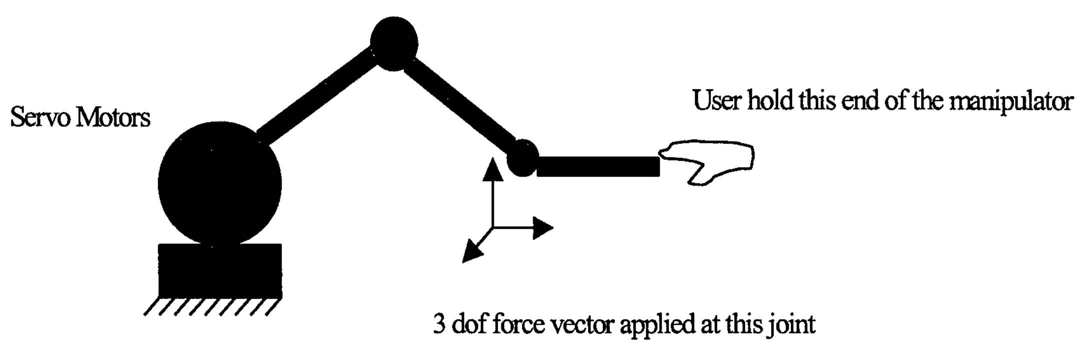

Figure 3. Schematic of the PHANToM device

In a typical application, the PHANToM is used to display contact forces between two physical objects. Collision detection is used to determine when objects are in contact. The corresponding reaction force vector is calculated and then applied. The PHANToM device supports six degrees of freedom as an input device (position and orientation) and three degrees of freedom as an output device (force vector). In the case of the electrostatic forces, we have a force field where the relative position, orientation and potential difference between two or more objects create an attractive force to be displayed by the PHANToM.

These forces can easily be applied using the PHANToM by integrating the interpolation code to look up the necessary force vector for current position of the tool. When the assembly tool come into contact with the MEMS component, the potential difference between the two object is zero, thus, the electrostatic forces between the two objects are zero. At this point we are no longer using a force field. Instead, the reaction force due to the contact of the tool with the MEMS component is the force displayed with the PHANToM (Figure 4).

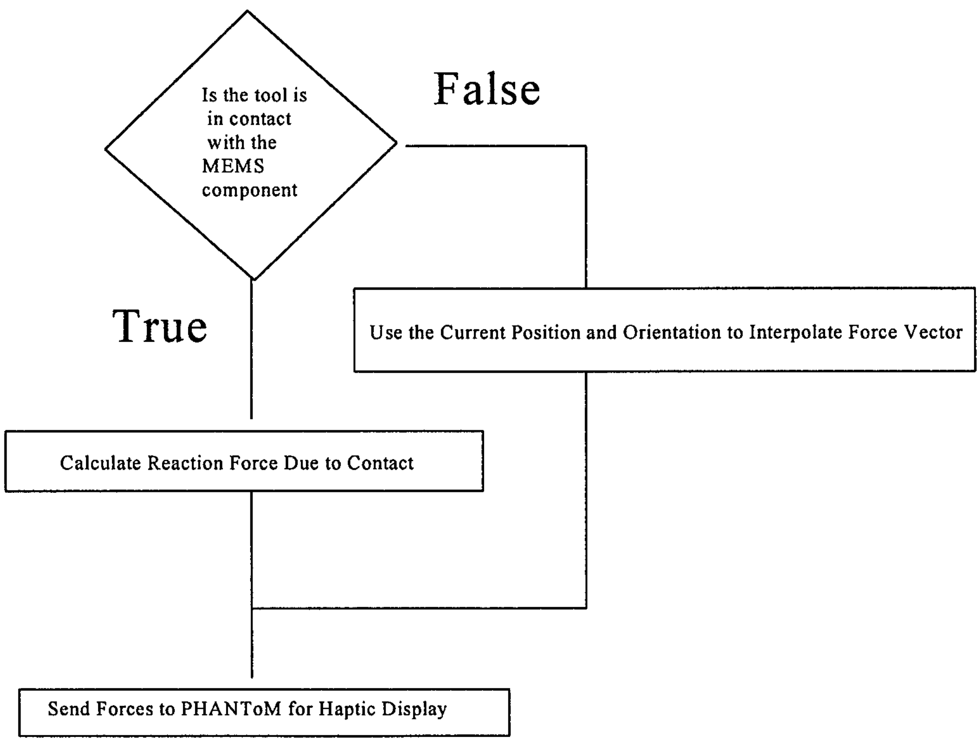

Figure 4. Choosing the type of force to be displayed

Several generic methods were created to use the Phantom and the CyberGrasp (from Virtual Technologies) to display various types of forces. These methods were used to create the integrated prototype application in task 8.

2.6 Task 6: Create a "virtual microscope" to allow a true evaluation of what the assembly operator or assembly robot will "see" during the real assembly process

A virtual microscope was created using a pair of Tektronix EXD-100 display tubes and the associated optics (Figure 5). In order to recreate the realism of a microscope, two different approaches were used to "de-focus" the image. The low depth of field and the image blur rendered a realistic virtual microscope image which was integrated into the final application.

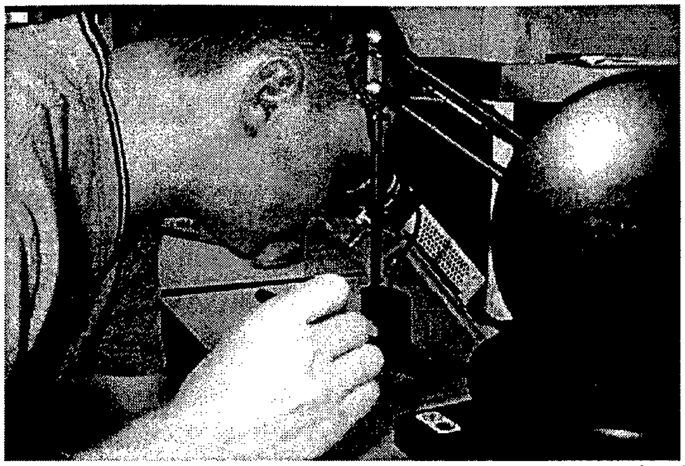

Figure 5. Using the PHANToM and the virtual microscope to manipulate the tweezers

2.7 Task 7: Evaluate the data requirements for the physically-based modeling of In2m assembly process and investigate if these data can be obtained from CAD systems

The data requirements for the calculation and display of forces of interaction in In2m assembly are primarily geometric. The surface geometry of the object is required for the electrostatic force calculations and for the detection of proximity and collision. The center of mass, moments of inertia, and other volumetric properties are required for simulating the response of the object subject to these forces. All of the geometric and volumetric information can be extracted from most CAD systems. The VADE application automatically extracts all of this information from the CAD system for simulating gravity induced motion.

2.8 Task 8: Integrate all of the above tasks into a proof-of-concept application

An integrated prototype application was created based on the above-described tasks. This application allows a user to view the assembly process in the virtual microscope while manipulating a part with a tweezer. Haptic feedback is provided through the Phantom. The electrostatic forces are pre-computed for a region and interpolation techniques are used to display the real-time forces during assembly.

References

[Arai 1995] R. Arai, D. Ando, T. Fukuda, Y. Nonoda, T. Oota, "Micro Manipulation Based on Micro Physics - Strategy Based on Attractive Force Reduction and Stress Measurement," *Proc. of ICRA 1995*, pp. 236-241.

[Ballandras 1997] S. Ballandras, S. Basrour, L. Robert, S. Megtert, P. Blind, M. Rouillay, P. Bernede, W.

[Dai 1998] F. Dai, "Virtual Reality for Industrial Applications", Springer-Verlab Berlin Heidelberg, 1998.

Daniau, "Microgrippers fabricated by the LIGA technique," Sensors and Actuators A 58 (1997) 265-272.

[Chandrana 1997] H. Chandrana, "Assembly Path Planning Using Virtual Reality Techniques", M.S. Thesis, Washington State University, 1997.

[Connacher 1996] H. Connacher, "Virtual Assembly Design Environment", M.S. Thesis, Washington State University, 1996.

[Fearing 1995] R.S. Fearing, "Survey of Sticking Effects for Micro Parts Handling," *Proc. of IROS '95*, Pittsburgh, PA, August 1995, Vol. 2, pp. 212-217.

[Feddema 1997] J.T. Feddema, C.G. Keller, R.T. Howe, "Experiments in Micromanipulation and CAD-Driven Microassembly," *Proc. of SPIE Vol. 3209*, pp. 98-107, Pittsburgh, Oct. 14-15, 1997.

[Feddema 1998a] J.T. Feddema, M. Polosky, T. Christenson, B. Spletzer, R. Simon, "Micro-Gripper for Assembly of LIGA Parts," *Proceedings of the World Automation Congress '98*, pp. ISORA-045.1 to 045.8, Anchorage, May 10-14, 1998.

[Feddema 1998b] J.T. Feddema, P. Xavier, R. Brown, "Assembly Planning at the Micro Scale," *Workshop on Precision Manipulation at the Micro and Nano Scales, 1998 IEEE International Conference on Robotics and Automation*, pp. 56-69, Leuven, Belgium, May 16-20, 1998.

[Feddema 1998c] J.T. Feddema, R. W. Simon, "CAD-Driven Microassembly and Visual Servoing," *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*, Leuven, Belgium, May 16-20, 1998, pp. 1212-1219.

[Feddema 1998d] J.T. Feddema, R.W. Simon, "Visual Servoing and CAD Driven Microassembly," *IEEE Robotics and Automation Magazine*, pp. 18-24, December 1998.

[Feddema 1998e] J.T. Feddema, "Microassembly of Micro-Electro-Mechanical Systems (MEMS) using Visual Servoing," *The Confluence of Vision and Control*, ed. Kriegman, Hager, and Morse, Springer-Verlag London Limited, 1998.

[Feddema 1999] J.T. Feddema, T. Christenson, "Parallel Assembly of LIGA Components," *Tutorial on Modeling and Control of Micro- and Nano-Manipulation, 1999 IEEE International Conference on Robotics and Automation*, Detroit, May 11, 1999.

[Jayaram 1997] S. Jayaram, H. Connacher, K. Lyons, "Virtual Assembly Using Virtual Reality Techniques", *CAD*, Vol. 29, No. 8, 1997.

[Jayaram 1999] S. Jayaram, Y. Wang, U. Jayaram, K. Lyons, P. Hart, "A Virtual Assembly Design Environment", Proceeding of IEEE Virtual Reality 99, Houston, March 1999.

[Jones 1996] R. Jones and R. Wilson, "A Survey of Constraints in Automated Assembly Planning", Proceedings of IEEE International Conference on Robotics and Automation, 1996.

[Jones 1997] R. Jones, R. Wilson, T. Colton, "Constraint-Based Interactive Assembly Planning", IEEE International Conference on Robotics and Automation, 1997.

[Keller 1997] C.G. Keller, R.T. Howe, "Hexsil Tweezers for Teleoperated Micro-Assembly," *Proc. MEMS97*, 1997.

[Koyano 1996] K. Koyano, T. Sato, "Micro Object Handling System with Concentrated Visual Fields and New Handling Skills," *Proc. of ICRA 1996*, pp. 2541-2548.

[Mitsuishi 1996] M. Mitsuishi, N. Sugita, T. Nagao, Y. Hatamura, "A Tele-Micro Machining System with Operation Environment Transmission under a Stereo-SEM," *Proc. of ICRA 1996*, pp. 2194-2201.

[Miyazaki 1996] H. Miyazaki, T. Sato, "Pick and Place Shape Forming of Three-Dimensional Micro Structures from Fine Particles," *Proc. of ICRA 1996*, pp. 2535-2540.
[Oliver 1995] J. Oliver, R. Kuehne, "A Virtual Environment for Interactive Assembly Planning and Evaluation", Proceedings of ASME Design Automation Conference, 1995.
[Rosen 1998] D. Rosen, Z. Siddique, M. D. Bauer, "A Virtual Prototyping System for Assembly, Disassembly, and Service", ASME 1998 Design Engineering Technical Conferences, Atlanta, Georgia, September 1998.
[Sulzmann 1995] A. Sulzmann, H.-M. Breguett, J. Jacot, "Microvision System (MVS): a 3D Computer Graphic-Based Microrobot Telemanipulation and Position Feedback by Vision," *Proc. of SPIE Vol. 2593*, Philadelphia, Oct. 25, 1995.
[Seywald, 2000] H. Seywald, "Extrapolation of Electrostatic Forces and Moments for Micro Electro Mechanical Systems (MEMS)", AMA Report No. 00-11, Analytical Mechanics Associates, Inc., June 2000.
[Tirumali 1999] H. Tirumali, "Tools and Two-Handed Assembly in VADE", M.S. Thesis, Washington State University, to be completed in May 1999.
[Wang 1998] Y. Wang, "Physically Based Modeling in Virtual Assembly", Ph.D. Dissertation, Washington State University, 1998.
[WWW01] http://www-mtl.mit.edu/CAPAM/demo-pages/fastcap.html
[WWW02] http://intellis.com
[Zesch 1997] W. Zesch, M. Brunner, A. Weber, "Vacuum Tool for Handling Microobjects with a Nanorobot," *Proc. of ICRA 1997*, pp. 1761-1766.